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A comparative study of the moisture transfer properties and durability of PC and GGBS mortars.

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Abstract

Ground Granulated Blast-furnace Slag (GGBS) is commonly used partially replacing Portland cement (PC) in concrete. GGBS is a finely-grained, basic slag with hydraulic properties and a high specific surface, produced as a by product in metallurgy. A number of authors have studied the influence of GGBS addition on the properties of OPC mortars and concrete concluding that GGBS enhances the general performance of PC composites improving workability, reducing creep and drying shrinkage, raising the ultimate compressive strength and reducing bleeding and heat of hydration. GGBS has been reported to improve the pore structure of PC decreasing salt diffusion thus incresing durability. However the most relevant hygric properties of GGBS mortar have not yet been studied. This paper provides an account of the most relevant hygric properties of GGBS and PC mortars. It compares the permeability, capillary suction, water absorption and compressive stregth of PC mortars incorporating GGBS in different proportions and studies how these properties vary as the mortars are subjected to artificial weathering in the laboratory. According to the results obtained, the PC mortars showed greatest permeability, water absorption and capillary suction and lower compressive strengths than the GGBS mortars. The PC mortars also showed the greatest rise in permeability, water absorption, capillary suction and mass loss as well as the greatest decrease in compressive strength as a result of weathering. According to these results, the addition of GGBS to OPC composites lowers the water absorption, capillary suction and permeability simultaneously increasing ultimate compressive strength and durability. This may be due to both the geometric characteristics and reactivity of the GGBS that allow a greater density and lower permeability due to the tight packing of the mortar's microfabric as well as the presence of abundant early hydraulic cements.

Keywords: capillary suction, compressive strength, durability, GGBS, OPC, permeability, water absorption.

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INTRODUCTION

Blastfurnace slag (BS) is a by product of the steel industry. It is formed by the combination of iron ore with limestone flux and obtained from the manufacture of pig iron in a blastfurnace. When BS is quenched by water it forms a glassy material known as granulated blastfurnace slag (GBS). In contact with water, like Portland cement, GBS possesses hydraulic properties. However, the rate of reaction is slow and needs alkalis to activate. When GGBS is mixed with Portland cement (PC), the PC hydrates releasing lime, the alkali that serves as an activator for the GGBS.

The chemical composition of GGBS together with its particle size and morphology are important as these will determine GGBS reactivity thus significantly affecting the final properties of concrete. GGBS has the same constituents as Portland cement but in different amounts (Table 1). In general, the more alkali slags are, the greater their hydraulic activity in the presence of alkalis. Swamy [1] has suggested that at constant PH, strength of the concrete increases with the Al_2O_3 content. Traces of chlorine (Cl) or sulphur (S) may also be found in GGBS. These can react with one of the mineralogical phases of Portland cement clinker, tri-Calcium Aluminate (C_3A) to form an expansive compound. In order to avoid this problem, the British Standards only allow a Cl or S content of 1%.

Table 1. Chemical Composition of GGBS and OPC after Bakherev [2].

Chemical composition %	OPC	GGBS
SiO_2	20.10	35.04
Al_2O_3	4.15	13.91
Fe_2O_3	2.50	0.29
CaO	61.30	39.43
MgO	3.13	6.13
K_2O	0.39	0.39
Na_2O	0.24	0.34
TiO_2	0.24	0.42
P_2O_5	<0.90	<0.10
MnO	-	0.43
SO_3	4.04	2.43

A number of authors have studied the influence of GGBS addition on the properties of OPC mortars and concrete concluding that GGBS enhances the general performance of PC composites improving workability, reducing creep and drying shrinkage, raising the ultimate compressive strength and reducing bleeding and heat of hydration.

According to Swamy [1], GGBS enhances concrete workability due to its surface properties and fineness (approximately 460 Blaine (m^2/kg.min)). According to this author, this makes GGBS 2-3 times finer than Portland cement, leading to an enhanced workability and a better performance in bleeding, setting times and heat evolution. However Becknell and Hale [3] state that slump does not significantly increase with increasing substitution of OPC by GGBS, concluding that GGBS does not significantly affect concrete workability.

In relation to permeability, these authors demonstrated that GGBS replacement consistently decreased permeability measured by chloride ion penetrability, and that the higher the amount of GGBS the lower the permeability. Kumar et al. [4] found that the porosity of GGBS enhanced concrete is about one half and the pore size one third of that of a corresponding PC sample. It has also been demonstrated that GGBS improves the general performance of PC composites decreasing chloride diffusion and chloride ion permeability [5], [6]); reducing creep and drying shrinkage [7]; increasing sulphate resistance ([8~~], ~~[9]); enhancing the ultimate compressive strength (Barnett et al. [10]) and reducing the heat of hydration and bleeding (Wainwright and Rey [11]). In relation to durability, Kumar et al. [4] proved that GGBS concrete is better at both resisting chloride ingress and alkali-silica reactions than PC concrete. In addition, Becknell and Hale [3] demonstrated that the addition of 20%GGBS grade 120 increases the freeze-thaw durability of concrete by 5 times when compared to that of a 100%OPC mix while 40% GGBS replacement increases the durability by 8 times and, in contrast, an increase in durability was not apparent with a replacement rate of 60%.

In relation to strength, it is generally accepted that GGBS raises the ultimate strength of OPC mortars and concrete. However, Barnett et al. [10] demonstrated that the early (3-day) strength of GGBS concrete is significantly lower than that of OPC concrete, and that the 28-day strength was very similar to that of OPC concrete and approximately the same for all GGBS replacement levels (0, 35 and 70%). In addition, testing by Becknell and Hale [3] showed that replacement of OPC with grade 120 GGBS increases the 28-day compressive strength at the replacement rate of 20% however, 40% replacement slightly lowered the compressive strength while 60% replacement lowered it further. These authors obtained opposite results when using GGBS of a different grade (100). In this case 20% GGBS content mixes showed a lower strength than the OPC mix while 40% and 60% showed progressively increasing values.

The purpose of this paper is to compare the moisture transfer properties and compressive strength of OPC mortars and mortars incorporating GGBS in different proportions, and to study how these properties vary as the mortar weathers, and whether these properties follow the trends established by former investigators.

MATERIALS AND METHODS

GGBS analysis by SEM and EDX

The morphology of the GGBS used was observed under the Scanning Electron Microscope (SEM). The analytical system employed was a Zeiss DSM-950 scanning electron microscope equipped with a backscattered electron detector and a LINK-QX 2000 energy dispersive X-ray analysis attachment (EDX). Quantitative chemical composition spectra were taken with a voltage of 20 Kv. through a beryllium window. The particle size distribution of the GGBS was also assessed with the SEM.

Mix Composition and Mixing

Ordinary Portland cement supplied by Irish cement was used as a binder in all samples. The samples were mixed according to I.S. EN 206-1:2002 [12] and BS 4551 [13]. It was decided to use cubes with 100%OPC, 70%OPC / 30%GGBS and 50%OPC / 50%GGBS in order to test the effect of increasing GGBS amounts. Water was added to each mix according to the moisture content of the sand measured using a Speedy test. Thirteen 100mm cubes were made from each mix. The moulds were filled and compacted using a vibrating table. They were covered with hessian sacking and left for 24 hours to set. The mortars were then released from the moulds, labelled and placed in a curing tank. Samples tested include unweathered OPC and GGBS samples as well decayed samples at the different weathering stages reached during the course of a durability test.

Table 2: Composition of mixes tested.

Mix proportions	OPC (kg)	Sand (kg)	Water (kg)	GGBS (kg)
100% OPC	4.55	24.05	2.6	-
70%OPC / 30%GGBS	3.185	24.05	2.6	1.385
50%OPC / 50%GGBS	2.275	24.05	2.6	2.275

Durability test by immersion in organic acid solution

A synthetic solution containing the key components of farmyard silage effluent was prepared according to O'Donnell et al. [14]. The composition of this solution is included in Table 3. The pH of the solution was adjusted to 4.0 by adding the hydroxides of cations (K^+, Na^+, Ca^{2+}, Mg^{2+}) in the relative proportions specified by the aforementioned authors.

Table 3: Chemical composition of the synthetic silage effluent.

Constituent	Amount g/kg
Lactic acid	15
Acetic Acid	5
Formalin (0.38% w/w formaldehyde)	3
KOH	3.67
NaOH	0.78
$Ca(OH)_2$	1.39
$Mg(OH)_2$	0.44

The samples were subject to three, 28-day [14] immersion cycles and the moisture properties measured at different intervals. Four cubes of each mix, were immersed in the solution.

Permeability test

Permeability determines the durability of a mortar as the less permeable the mortar, the fewer destructive substances will be able to penetrate it. This property was measured with the Autoclam test [15]. A base ring was fixed onto the surface of the sample isolating a test area with a diameter of 50 or 75 mm. A constant pressure of 0.5 bars was applied to contribute to the rate of flow across this area. The flow of water into the specimen was recorded automatically every minute for 15 minutes, with a data collector attached to the Autoclam. The total volume of water penetrating into the concrete was recorded in m^3 and plotted flow versus the square root of time informing on the material's permeability. In most instances this should yield a straight line graph, the slope of which may be reported as a Water Permeability Index (WPI) with units $m^3/\sqrt{min}$.

Capillary test

The capillary tests were performed in accordance with BS EN 1925:1999 [16]. The purpose of this test is to determine how much fluid will enter into the mortar through suction forces created by the water molecules and their micro connections with pore walls. The more fluid is able to enter the mortar through capillary action the more susceptible it will be to attack by silage effluent. The area of the base of each cube was calculated. The samples were then placed on thin supports and submerged to a constant depth of 3±1mm. At time intervals (first at 1 minutte followed by readings every 10 minuttes), for a total of 45 minutes, the cubes were removed, blotted dry and weighed. The water suction was calculated using Eq.1:

$$S = (W_s - W_d / A) * 100 \qquad \text{Eq. (1)}$$

Where:

S = Suction ($g/cm^2.min$)
W_s = Final weight after submersion after one minute (g)
W_d = Initial dry weight of cube (g)
A = Area (cm^2)

Water absorption test

This test was carried out in order to find out whether there was an increase in pore space in the mortars as a result of GGBS replacement and weathering. This test was carried out in accordance with UNE standards [17]. The dry mass of the samples was first noted. The mortars were immersed in water, at atmospheric pressure until saturation. Water absorption was measured as a percentage of the saturated mass of the specimen using Eq. 2 below:

$$Wa = (W_s - W_d / W_s) * 100 \qquad \text{Eq. (2)}$$

Where:

Wa = Water absorption
W_s = Final weight after absorption
W_d = Initial dry weight

RESULTS

SEM/EDX Analysis

The morphology of the GGBS was observed with the SEM (Fig.1). The GGBS consists of microsized angular particles. The particle size distribution ranges between approximately 1 and 60 microns. Approximately 40-50% of the particles (% by volume) are sized close to 1 micron.

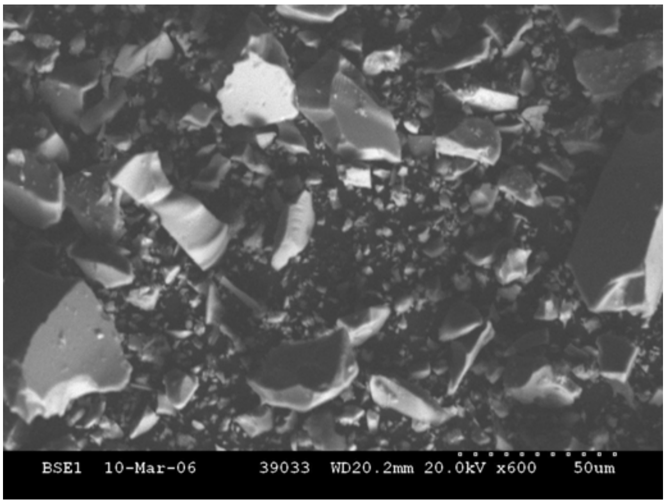

Figure 1. Microphotograph of SEM showing the morphology and size of the GGBS particles.

The spectrum of the quantitative chemical analysis by EDX is included in Fig. 2. The quatitative elemental composition of the GGBS is included in Table 4. This evidenced the presence of high amount of Calcium and Silicon and small amounts of Sulphur.

Table 4. Quantitative chemical composition of GGBS analysed with EDX.

Element	%
Mg	4.37-5.37
Al	6.86-7.59
Si	20.04-21.31
S	2.34-2.18
Ca	51.98-38.74
Ti	1.70-1.06

O	12.71-23-73

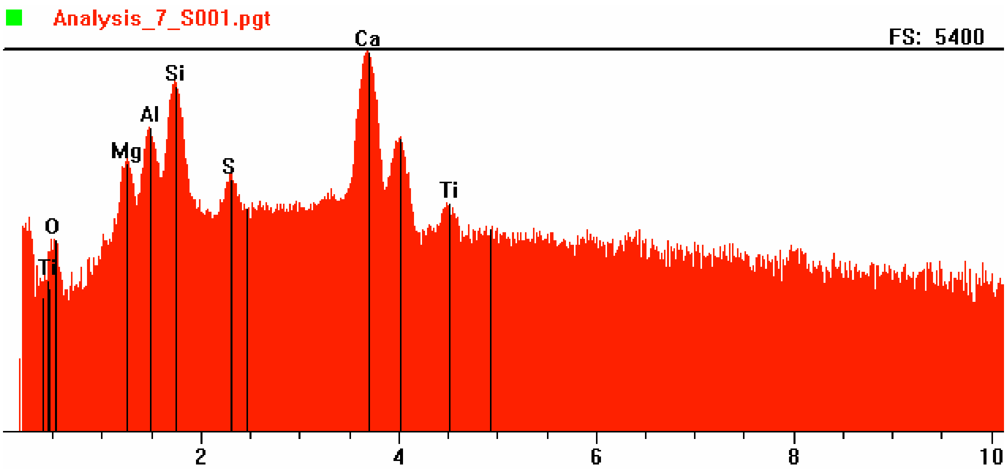

Figure 2. EDX spectrum of quantitative chemical analysis of GGBS analysed.

Durability test by immersion in organic acid solution

Over the course of the experiment it became clear that the OPC samples had degraded significantly more than their GGBS enhanced counterparts as the aggregate could be clearly seen protruding through the corroded cement paste. The increase of surface roughness of the 100% OPC samples was far greater than that of the 50% and 30% GGBS mortars. Very little surface degradation and material loss took place to the 50% GGBS samples.

Permeability

All samples showed an increase in permeability over the course of the experiment (Fig. 3). Although the permeability of the GGBS samples increased, their values were much lower than those reached by the PC samples. It is also clear from Fig. 3 that the WPI decreases with increasing amounts of GGBS. It can also be noted that, at the second stage of the experiment (i.e. following completion of the first 28-day weathering cycle), there is a dip in the WPI. This was probably due to the crystallization of salt in mortar pores blocking the pathway for water ingress thus providing a lower WPI. However, once the samples were washed, the increase in the WPI for each proceeding stage was significant and relatively linear. Clearly, the permeability increase rate is greater for the PC samples than for those containing GGBS.

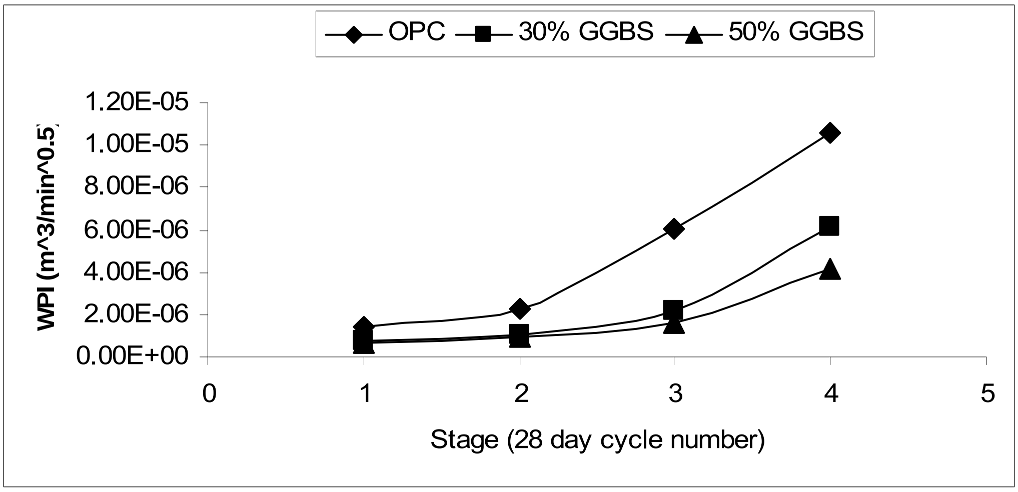

Figure 3. Average WPI for GGBS and PC samples at each stage of the weathering experiment.

Water Absorption

The results in Fig. 4 suggest that the higher the GGBS content the lower the amount of water absorption. This is also evidenced in Table 5 which shows the increase in water absorption between the first and last stage of the weathering experiment as a percentage. An increase of water absorption is directly related to an enhancement in pore space in the mortars as a result of weathering.

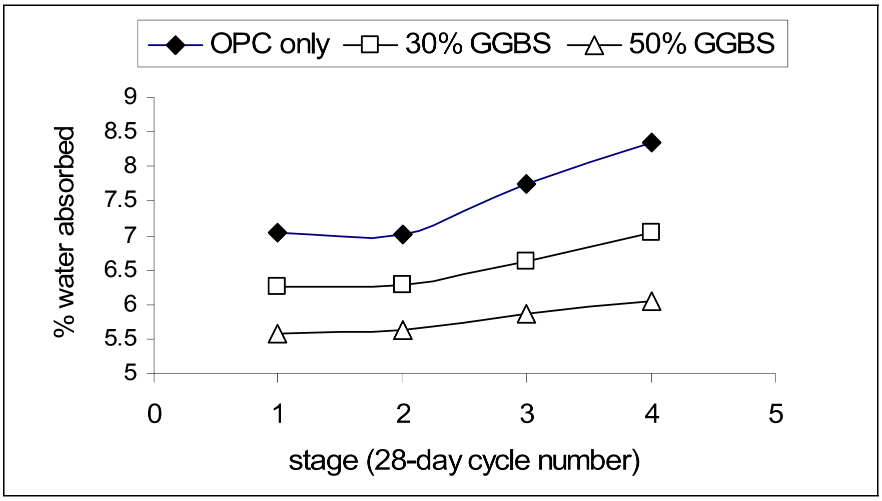

Figure 4. Water absoption of PC and GGBS samples.

Table 5. % Increase in water absorption between the first and last stage of the weathering experiment.

Mix type	% average increase in water absorbed
100% OPC	18.65
30% GGBS	12.65
50% GGBS	8.26

Capillary Test

The higher the amount of water suction exerted by the pores of a particular sample, the more susceptible it would be to degradation and hence the less durable it would be deemed. There is a sharp increase in water suction over the duration of the weathering experiment for all samples (Fig.5). Capillarity is measured by assessing the amount of water absorbed into the sample within the first minute. As a result, the immediate surface of the sample is most responsible for the figure obtained. It can, therefore be assumed that the immediate surfaces of all samples underwent some amount of degradation meaning that more pores had appeared towards the surface. At the first stage of the experiment, the higher the GGBS content in a sample, the higher the water suction. This may be due to smaller pores creating a higher suction force in the denser GGBS samples. It must be noted, however, that samples made from 100% Portland cement showed the greatest increase in water suction over the course of the experiment.

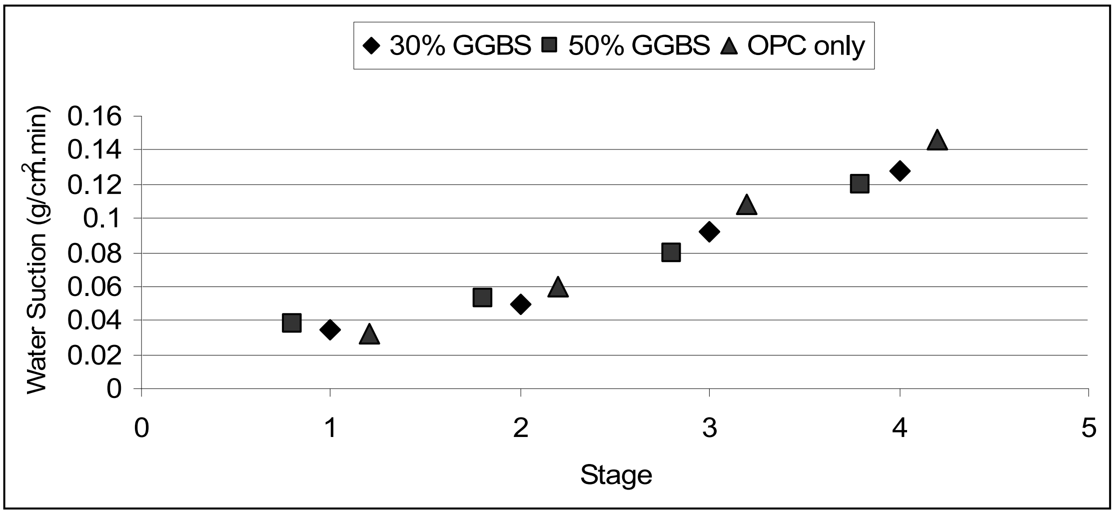

Figure 5: Average capillary suction of PC and GGBS samples at each 28-day, weathering cycle.

Compressive Strength

Mechanical strength is a good indicator of long term concrete durability, and it is generally accepted that stronger concretes will have a longer life. At the end of the weathering experiment, mortar mixes containing GGBS performed better, showing a greater strength than those including 100% PC (Table 6). This is probably due to the cements produced by GGBS. These cements have a greater proportion of strength-enhancing compounds and less lime (which contributes little to concrete strength) than those produced in the hydration of PC. The percentage loss in strength of the 100% PC samples was nearly twice as much as that of the 50% GGBS samples.

Sample	Average compressive of reference samples (unweathered) (N/mm^2)	Average loss in compressive strength after weathering experiment (N/mm^2)	% loss in compressive strength after weathering
100% OPC	15.09	7.05	46.74
30% GGBS	17.67	5.79	32.74
50% GGBS	18.81	4.11	21.82

Table 6. Compressive strength of unweathered samples and strength loss as a result of weathering.

CONCLUSION

All PC and GGBS samples showed an increase in permeability, water absorption and capillary suction as a result of weathering. However, the rate of increase as well as the final values reached are greater for the PC samples than for those containing GGBS. For example, samples containing 100% PC had the greatest rise in permeability, water absorption and capillary suction; the greatest loss in mass and the greatest decrease in compressive strength over the course of the weathering experiment. In addition, the results also evidenced that the durability of the mortars, when subjected to weathering cycles, increased with raising amounts of GGBS. This suggests that the low values of the moisture transfer properties of the GGBS mixes may be one of the reasons why GGBS mixes are more resistant than OPC mixes in aggressive environments.

According to the results obtained, the addition of GGBS to OPC composites lowers the water absorption, capillary suction and permeability simultaneously increasing ultimate compressive strength and durability.

The results showed significant differences in the values reached by the 30% and 50% GGBS mixes in both mass loss and water absorption. Nevertheless, in other properties such as capillarity and permeability there were no significant differences between the 30% and 50% mixes. In addition, at the end of the weathering experiment, mortar mixes containing GGBS showed a greater strength than those including 100% PC, and the percentage loss in strength of the 100% PC samples was nearly twice as much as that of the 50% GGBS samples.

The low moisture transfer values of the GGBS mortars may be due to both the microstructure and reactivity of the GGBS cement paste. The SEM analysis of GGBS revealed that it consists of angular particles sized between 1 and 60 microns, and that approximately half of these particles are close to 1 micron in size. The high specific surface and fineness of these GGBS particles can induce high reactivity and allow tight packing of a composite's microfabric, with low amounts of micropores and subsequently a greater density and lower permeability. This agrees with other authors. For example, Gao et al. [18] report that the pozzolanic reaction of GGBS starts at a very early age (producing hydraulic cements that seal pores) and that GGBS significantly decreases the size and content of $Ca(OH)_2$ crystals in the aggregate-paste interface which makes the microstructure of the interfacial transition zone aggregate/binder more dense. The ultimate reason for the higher strength of the GGBS mixes may also lay in the characteristics of the GGBS particles. This would explain contradictory strength results obtained by previous authors [3,10]. According to Wan et al. [19], the strength of GGBS mortar depends on both the surface area and the particle size distribution of the GGBS: the higher the amount of fine GGBS (particles <3μm) the higher the early strength while the higher the amount of particles sized 3-20 μm the higher the long-term strength.

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